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**SPONTANEOUS REIGNITION  
OF PREVIOUSLY EXTINGUISHED  
SOLID PROPELLANTS**

*by Carl C. Ciepluch*

*Lewis Research Center  
Cleveland, Ohio*

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**NATIONAL AERONAUTICS AND SPACE ADMINISTRATION**

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## SPONTANEOUS REIGNITION OF PREVIOUSLY

## EXTINGUISHED SOLID PROPELLANTS

by Carl C. Ciepluch

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## SUMMARY

The spontaneous reignition phenomenon associated with the extinction of solid propellants by sudden depressurization was investigated experimentally. The results indicated that many solid-propellant compositions may be susceptible to the reignition phenomenon; however, the occurrence is a function of the operating conditions. All propellant compositions exhibited a minimum ambient pressure limit below which reignition was not obtained. Decreasing the characteristic time for the expansion, defined as the time required for the pressure to reach 50 percent of its initial value, suppressed the tendency for reignition to occur. The reignition phenomenon was apparently controlled by a mechanism similar to that which is believed to occur in the initial ignition of solid propellants; the residual chamber combustion gas and the residual heat in the propellant surface were apparently the primary sources of ignition energy.

## INTRODUCTION

The ability to stop combustion in a solid-propellant motor without destruction of the assembly would be useful for stop-restart and for large booster abort requirements. A technique for extinguishing combustion that offers promise consists of a rapid depressurization of the combustion chamber. In order to gain a better understanding of the mechanisms associated with this process, a research program is being conducted at the Lewis Research Center. Previous investigations (refs. 1 and 2) have shown that there is a reproducible characteristic time for the expansion process, defined as the time required for the pressure to reach 50 percent of its initial value, below which extinction of combustion is always achieved. It was also shown that this expansion time for extinction was substantially affected by the propellant composition and decreased slightly as the initial chamber pressure increased.

On many occasions, however, depending on the conditions of the test, a particular propellant would reignite some time after it had been extinguished. Since this reignition phenomenon would vitiate the usefulness of the extinction process and little information had been reported on this subject, an experimental study of this phenomenon was undertaken and is reported herein. The experimental apparatus was similar to that used in reference 1 and consisted of a simple slab burner. The burner was mounted in an altitude chamber in which the ambient pressure could be varied from 1 to 0.005 atmosphere. Measurements were made of the rate of chamber pressure decrease, and the reignition phenomenon was detected by means of a photoelectric tube.

## APPARATUS AND PROCEDURE

The burner configuration used in this investigation is shown in figure 1 and was similar to that used in reference 1. The propellant charge consisted of a 3- by 5- by 1-inch slab, which was allowed to burn on only one of its large sides; 3/8 inch of propellant was consumed before the chamber was depressurized. A chamber orifice was used to provide the desired constant pressure prior to depressurization. The pressure decay transient was initiated by suddenly opening a chamber vent. Variation in the characteristic time for the expansion was accomplished by varying the vent size. The venting mechanism was modified from that reported previously in reference 1 in order to reduce the time required for the vent to open fully. These modifications included reducing the vent cover and pivot arm weight and increasing the vent cover size, which increased the vent opening force. As a result of these modifications, the time required for the vent to open fully was negligible, and this produced a very sharp initial change in chamber pressure. A quartz window was located on the chamber for observation of the combustion luminosity by means of a photoelectric tube. Combustion gases were exhausted to an altitude chamber in which the pressure could be varied from 1 to 0.005 atmosphere.

The propellant compositions investigated were as follows:

Propellant	Composition, weight percent				Flame temperature, °R	Constants in burning-rate equation	
	Binder	Ammonium perchlorate	Aluminum	Magnesium oxide		(d)	
	(a)	(b)	(c)			K	n
A	21.3	78.5	0	0.2	3930	---	---
B	18.8	81.0	0	.2	4340	0.0593	0.240
C	13.8	86.0	0	.2	5140	.0795	.251
D	18.8	72.0	9	.2	4920	.0324	.337

<sup>a</sup>Epoxy cross-linked copolymer of butadiene and carboxylic monomer (similar to binder commonly called PBAA).

<sup>b</sup>A blend of nominally 70 percent of 89-μ and 30 percent of 11-μ powders as determined by a Micromerograph where 50 percent by weight was finer than indicated diameters.

<sup>c</sup>Particle size, 6.7 μ.

<sup>d</sup>Burning-rate equation:  $r = KP^n$ , where  $r$  is the burning rate in inches/sec and  $P$  is the pressure in lb/sq in. abs as determined for a pressure range from 400 to 1000 lb/sq in. abs.

The flame temperatures listed were calculated for a chamber pressure of 500 pounds per square inch absolute according to the methods described in

reference 3.

Combustion pressure was measured with a water-cooled flush-diaphragm pressure transducer, which had a natural frequency of 25,000 cps. The output of the transducer was amplified and recorded on an oscilloscope and also monitored with a direct-writing oscillograph recorder. The characteristic expansion time was defined as the period of time required for the chamber pressure to decrease to 50 percent of its original value. This expansion time was determined from the oscilloscope record instead of the oscillograph record, as was done in reference 2, in order to obtain higher accuracy. Comparable measurements indicated that the oscillograph readings were 10 percent high because of the inherently slower response of that type of instrument. The luminosity signal from the phototube was recorded on the oscillograph.

A simple strand burner with a window for observing the flame was used to determine the minimum combustion pressure of the propellants. Strands  $3/8$  inch square by 5 inches long were ignited in the burner at near-atmospheric pressure, and then the pressure was gradually diminished until the flame disappeared. The pressure in the chamber at the time the propellant was extinguished was observed on a vacuum gage.

## RESULTS

Typical pressure and luminosity records, which illustrate the reignition characteristics of both nonaluminized and aluminized propellant compositions, are shown in figure 2. In both examples the characteristic expansion time was below that required for extinction (ref. 2), and although the propellant was extinguished, it spontaneously reignited. This fact is best indicated by the luminosity records, which show that during the pressure decrease the luminosity dropped sharply to zero, which indicated extinction. The propellant remained extinguished for a period of 3.5 and 2.25 seconds for the nonaluminized and the aluminized propellants, respectively, before reignition occurred. The reignition point was determined by the first indication of a luminous flame on the luminosity record. In some cases this point was not distinct because of the gradual increase in luminosity during reignition. Once reignited, the remaining propellant was completely consumed except for very thin slivers. For conditions that resulted in extinction without any subsequent reignition, no indication of a luminous flame was observed after the depressurization. Examination of the amount of remaining propellant confirmed that extinction was permanent.

A region of unsteady combustion occurred with the aluminized propellant composition during the low-pressure burning period after reignition. The unsteady flame produced large oscillations in flame luminosity and only moderate oscillations in the chamber pressure. This unsteady combustion was regularly observed to occur only in the low-pressure range near atmospheric pressure and was obtained only with the aluminized propellant composition D. Apparently these oscillations are inherent in the combustion process, and they are not associated with the usual acoustic type of instability since the oscillation frequency range encountered is considerably lower than the natural acoustic frequency of the chamber. The oscillatory frequencies obtained with propellant composition D ranged from 10 cps at an ambient pressure of

1/4 atmosphere to 45 cps at an ambient pressure of 1 atmosphere.

The effects of both ambient pressure and expansion time on the occurrence of spontaneous reignition for composition D are shown in figure 3. The expansion time required for extinction is essentially constant and therefore unaffected by the range of ambient pressure variation encountered. The critical value of expansion time required to just extinguish combustion was approximately 3 milliseconds for the aluminized composition shown in figure 3. This value is about 16 percent lower than the value previously reported in reference 2 for essentially the same propellant composition. Although a small part of the reduction in critical expansion time may be due to changes in batches of the propellant components, the major reasons for this difference are felt to be the improvements in the transient pressure recording system and in the improved venting system as discussed in the APPARATUS section. The reignition phenomenon was first observed at approximately 1/4 atmosphere, and a sharp decrease in expansion time was required to prevent reignition. The pressure limit for reignition was then found to increase as the expansion time was decreased, which indicated that faster expansions tend to suppress reignition. Extrapolation of the boundary between the extinction and the extinction-and-reignition regions to a pressure of 1 atmosphere indicates that an expansion time of less than 0.5 millisecond should prevent reignition. Since the venting apparatus was limited to a minimum expansion time of 0.9 millisecond, this test condition could not be attained.

For those conditions that resulted in propellant reignition (fig. 3), the period of time for which the propellant remained extinguished increased as either the expansion time or the ambient pressure decreased; however, there was considerable scatter in the data. For composition D, which was most thoroughly investigated, the period of extinction increased from an average of 1 second to more than 20 seconds in some cases as the ambient pressure was reduced from 1 atmosphere to 1/4 atmosphere (near the reignition limit). As expected, the increase in extinction time was more pronounced as the reignition limit was approached since theoretically the extinction time is infinite at the reignition limit. An increase of several seconds in extinction time was observed when the time for expansion was decreased from 3.0 to 0.9 millisecond.

The ambient pressure at which reignition was first encountered was determined for several propellant compositions, and the values obtained are listed in table I. The minimum pressure at which reignition occurred was determined by a trial-and-error process requiring at least five runs to determine the value for each propellant composition to within limits of less than 3 or 4 percent. These values were obtained for expansion times approximately 20 percent lower than the critical value for extinction in order to have a common ground for comparison and to avoid ambiguity in the analysis of the results. The reignition behavior was sensitive to propellant composition. The aluminized propellant had the lowest reignition pressure limit. The running time did not influence the reignition point, but increasing the initial chamber pressure decreased the tendency to reignite.

The minimum pressure at which combustion could be self-sustained, as determined with the strand burner, was found to be 0.048 atmosphere for composition D and 0.043 atmosphere for composition B.

## DISCUSSION OF RESULTS

Variation in ambient pressure produced no noticeable effect on the initial extinction of combustion. This lack of effect was probably due to the fact that over the range of ambient pressure investigated there were relatively small changes in the pressure decay transient that occurred near the end of the expansion when the flow through the vent and the nozzle became subcritical. Accordingly, the lack of influence of ambient pressure on combustion extinction indicates that the propellant was probably extinguished before the subcritical point was reached.

While the self-sustaining combustion pressure limits were 0.048 and 0.043 atmosphere for compositions D and B, respectively, the minimum ambient pressure at which reignition was encountered was considerably higher than these values. It can therefore be reasoned that the reignition pressure limit is not a result of the normal combustion limit of the propellant itself but rather that this limit must be a function of the energy available for reignition of the propellant. In reference 4 the threshold energy flux required for ignition is shown to increase sharply as the pressure is decreased in the subatmospheric range. Accordingly, the reignition pressure limit must correspond with the point where the ignition energy required is greater than that which is available, and, consequently, reignition is not encountered. For some propellant compositions that may have either a relatively low ignition-energy requirement or a high combustion pressure limit, however, the combustion pressure limit may possibly determine the minimum pressure at which reignition is first encountered.

There are two potential sources of energy available for reigniting the propellant: the heated chamber walls and the hot combustion products remaining in the chamber after depressurization. In view of the large portion of the chamber walls that was exposed to convective heating during combustion, the radiative transfer of heat from these surfaces to the propellant once it has been extinguished could be a possible energy source contributing to reignition. Because of the relatively short burning times, however, the surface temperature of the chamber wall did not rise to a high value. The surface temperature of the chamber wall directly above the propellant surface was determined from the graphs presented in reference 5, with one-dimensional transient conduction assumed in the wall and convective heat transfer at the surface. This calculation was made for propellant composition D with the use of a convective heat-transfer coefficient of 53 Btu per hour per square foot per  $^{\circ}\text{F}$  and a gas temperature equal to 85 percent of the ideal flame temperature. The computed surface temperature of the 1/2-inch-thick wall was about 300 $^{\circ}\text{F}$  after a burning time of 1.5 seconds. Calculation of the black-body radiation for this surface temperature indicated that the energy transfer would amount to 600 Btu per hour per square foot. This calculated maximum rate of energy flux is insignificant when compared with the threshold radiant energy requirements measured for ignition at 1 atmosphere in reference 4, and radiant heat transfer therefore appears to play a small part in the reignition phenomenon. The results obtained for composition A with half the usual burning time support this conclusion. The resulting reduction in chamber-wall temperature rise should have produced a sizeable decrease in radiant flux because of its fourth-power dependence on temperature. There was no influence, however, on the minimum reignition pressure (table I). Although radiant energy flux apparently did not influence the reignition phenomenon in these

experiments, it may be important in cases where the temperatures of inert chamber surfaces are considerably higher than those in this study.

The temperature of the residual combustion gas after depressurization was calculated and was considerably higher than the autoignition temperature of the propellant, which is generally about 500° F. For composition D, for example, the combustion gas temperature was estimated to be 85 percent of the ideal flame temperature, and the residual gas temperature for this propellant was calculated to be approximately 1850° F if an adiabatic expansion from 500 pounds per square inch absolute to atmospheric pressure is assumed. Even though this gas temperature can be expected to be decreased somewhat because of dilution with propellant pyrolysis products during depressurization, the temperature of these gases would still be considerably greater than the propellant autoignition temperature and consequently could serve as an important energy source for reignition. The flow of heat from the residual gases to the propellant surface after extinction and after gas flow has halted will be primarily a result of conductive heat transfer.

If it is assumed that the residual chamber gas and propellant are in perfect thermal contact and that the thermal properties of each are constant, the change in surface temperature with time can be calculated by numerical integration for the one-dimensional heat conduction case as described in the appendix. The following properties were used in this calculation: gas temperature, 1850° F; gas thermal diffusivity, 3.43 square feet per hour; gas layer thickness, 0.1043 foot; propellant temperature, 70° F; propellant thermal diffusivity, 0.00696 square foot per hour; and propellant thickness, 0.0156 foot. The increase in propellant surface temperature was determined to be only 2° to 3° F for a heating time of 1 second, which was typical of the length of time required for reignition to occur for composition D at an ambient pressure of 1 atmosphere. Accordingly, it was concluded that heat transfer to the propellant surface from the residual chamber gas is not an important factor in the reignition mechanism.

It is therefore suggested that the reignition mechanism consists of a gas-phase ignition, similar to the mechanism proposed in reference 6, in which flammable pyrolytic gases, which are generated by residual heat in the propellant surface, are then heated to the ignition point by mixing with the residual chamber gas. The lack of information concerning the propellant pyrolysis rate after extinction precludes calculation of the time-dependent concentration and temperature of the pyrolyzed gases in order to determine the validity of this theory. Certain trends in the experimental results, however, tend to support this theory. For example, generally as the flame temperature increased (see table, p. 2), the reignition pressure limit was decreased, that is, the reignition tendency was increased (table I). A higher propellant flame temperature results in a correspondingly higher residual gas temperature for a given degree of expansion, and, consequently, the tendency to reignite would be expected to increase as was noted. Also, the residual gas temperature, and accordingly the reignition tendency, should be diminished by increasing the degree of expansion. This effect was noted with composition D, for which it was observed that the reignition pressure limit increased as the initial pressure was increased.

## SUMMARY OF RESULTS

The results of an investigation of the reignition phenomenon following extinction of solid-propellant combustion by sudden depressurization are summarized as follows:

1. All propellant compositions could be extinguished by sudden depressurization, provided that the characteristic time of the expansion process was less than a critical value; however, in some cases, depending on operating conditions, extinction was only temporary, and the propellants would spontaneously reignite.

2. For each propellant composition a minimum ambient pressure existed below which reignition was never obtained. This reignition pressure limit was considerably higher than the self-sustaining combustion limit.

3. Decreasing the expansion characteristic time increased the reignition ambient pressure limit and thereby suppressed the reignition tendency.

4. Analysis of the results indicated that the reignition phenomenon was similar to a previously proposed gas-phase ignition mechanism and that the energy required for ignition probably resulted from a combination of the residual heat in the propellant surface and the chamber gases.

5. The radiant energy from inert chamber walls was calculated to be insignificant and accordingly did not influence the reignition process.

## CONCLUDING REMARKS

The results of this investigation indicate that termination of combustion in solid-propellant motors will be significantly influenced by the ambient pressure. For combustion termination in space at extremely low ambient pressures, there appears little likelihood that any reignition will be encountered, and extinction will be relatively simple. Combustion termination in the atmosphere, however, will be more difficult to achieve because of the fast expansions required to avoid spontaneous reignition of the propellant. With propellant compositions that readily reignite, the use of a secondary coolant in conjunction with a rapid pressure decrease may even be necessary to ensure permanent extinction or to ease the venting mechanism requirements. Since there is usually a period of several seconds or more between extinction and reignition, a coolant or chemical quenching agent could be injected into the chamber during this period to prevent reignition. This coolant must be distributed and mixed properly so that either (1) the combustion gases remaining in the chamber are cooled to the point where they possess insufficient energy to promote reignition or (2) the propellant surface is cooled to decrease the pyrolysis rate and thereby to halt the generation of ignitable gases.

Lewis Research Center  
National Aeronautics and Space Administration  
Cleveland, Ohio, October 29, 1963

# APPENDIX - CALCULATION OF TRANSIENT SURFACE TEMPERATURE OF PROPELLANT

The numerical calculation is based on one-dimensional transient conduction from the chamber gas to the propellant. The equations are similar to those described in reference 7. Physical properties are assumed constant for both gas and propellant. The interface temperature is calculated as follows:

$$t'_i = \frac{t_{i-1} + \left( \frac{M_g}{2} + \frac{M_p R}{2} - 1 - R \right) t_i + R t_{i+1}}{\frac{M_g}{2} + \frac{M_p R}{2}}$$

where

K thermal conductivity

$$M = \Delta x^2 / \alpha \Delta \theta$$

$$R = \Delta x_g K_p / \Delta x_p K_g$$

t temperature

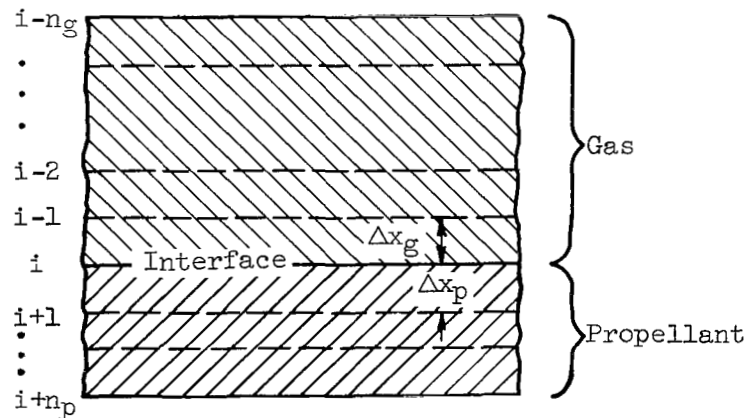
t' new temperature after increment in time  $\Delta \theta$

$\Delta x$  increment in thickness of gas or propellant layer

$\alpha$  thermal diffusivity

$\theta$  time

The subscripts g and p refer to the gas and the propellant, respectively; the subscripts i, i-1, and i+1 refer to the interface and to increments on the gas side and the propellant side of the interface, respectively, as shown in the following sketch:



Temperatures at increments in the gas and the propellant layers are determined as follows:

$$t'_{i-n} = \frac{t_{i-n-1} + (M_g - 2)t_{i-n} + t_{i-n+1}}{M_g}$$

$$t'_{i+n} = \frac{t_{i+n-1} + (M_p - 2)t_{i+n} + t_{i+n+1}}{M_p}$$

where  $n$  is the number of either gas or propellant increments starting from the interface. The temperature of the last increments is found as follows:

$$t'_{i-n} = t_{i-n} - \frac{t_{i-n} - t_{i-n+1}}{\frac{1}{2} M_g}$$

$$t'_{i+n} = \frac{t_{i+n-1} - t_{i+n}}{\frac{1}{2} M_p} + t_{i+n}$$

In these equations the value of  $n$  is taken as the total number of increments for either the gas or the propellant, depending on the equation being used.

At the starting condition ( $\theta = 0$  sec) the temperature gradient at the interface is infinite, and, therefore, an approximation must be made in order to start the calculation. Since the density of the propellant was several orders of magnitude greater than that of the gas, a large change in propellant temperature was not expected. As an approximation it was therefore assumed that the interface temperature was equal to the propellant temperature at zero time. This assumption was satisfactory since the calculation revealed only a several-degree rise in interface temperature under the conditions for which the calculation was made.

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TABLE I. - MINIMUM REIGNITION PRESSURE FOR VARIOUS  
PROPELLANTS AND OPERATING CONDITIONS

Propel- lant	Chamber pressure, lb/sq in. abs	Run time, sec	Ambient pressure at which reignition was first encountered, atm
A	500	1.4	0.626
		0.7	0.631
B	500	1.5	0.51
C	500	1.1	0.46
D	500	1.5	0.235
	1000	1.2	0.35

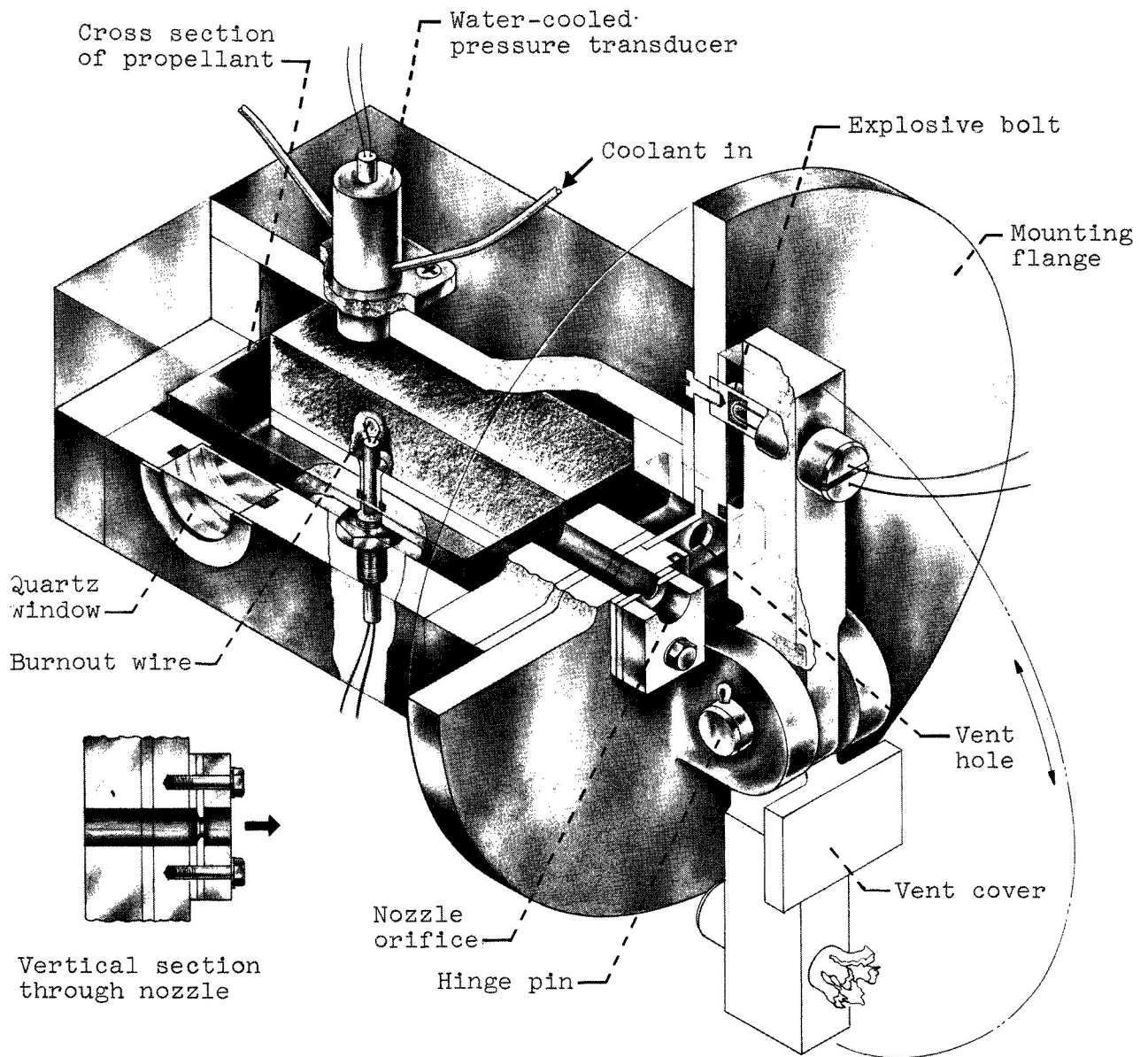


Figure 1. - Combustion-chamber assembly.

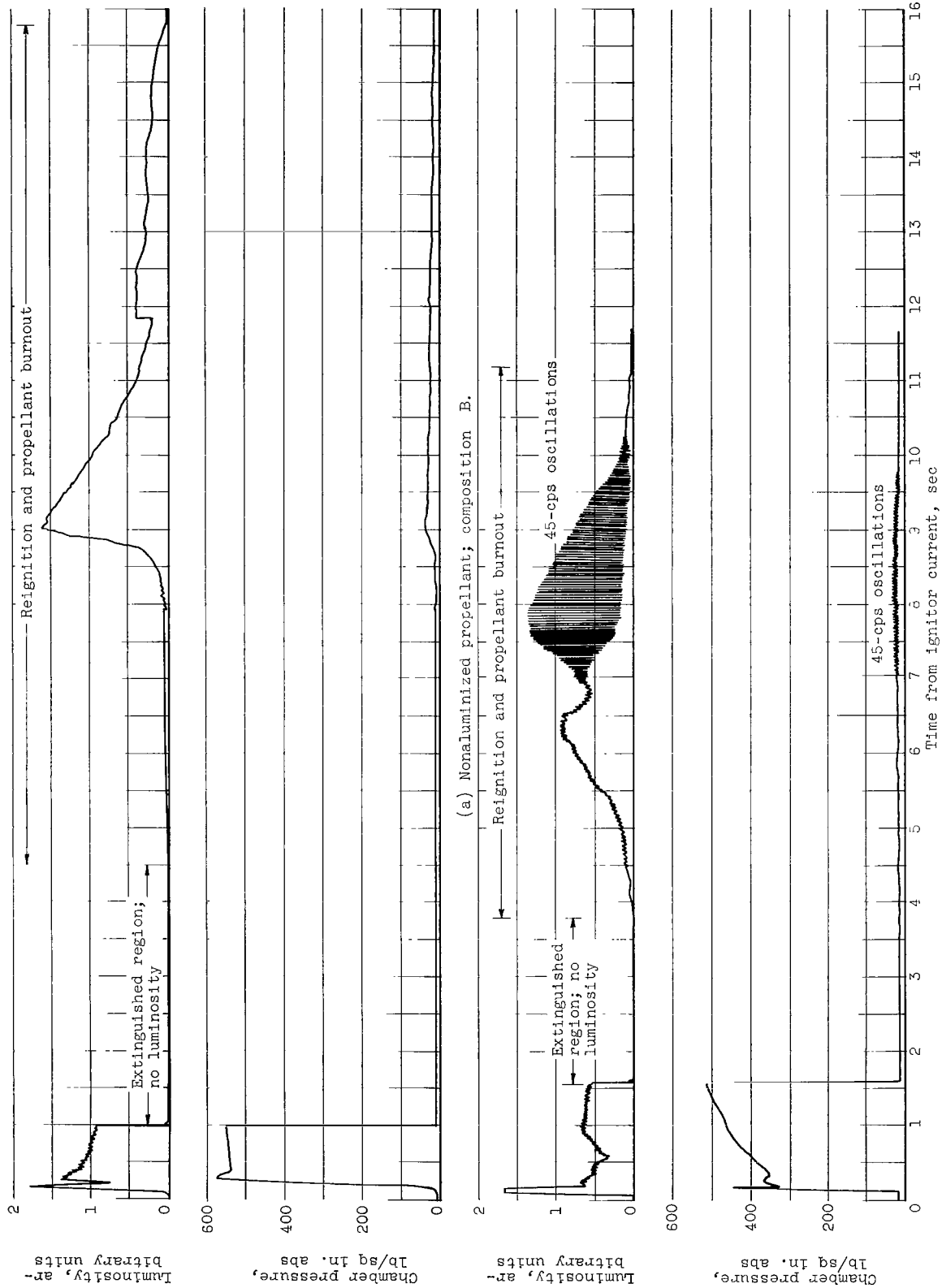


Figure 2. - Typical records of propellant reignition.

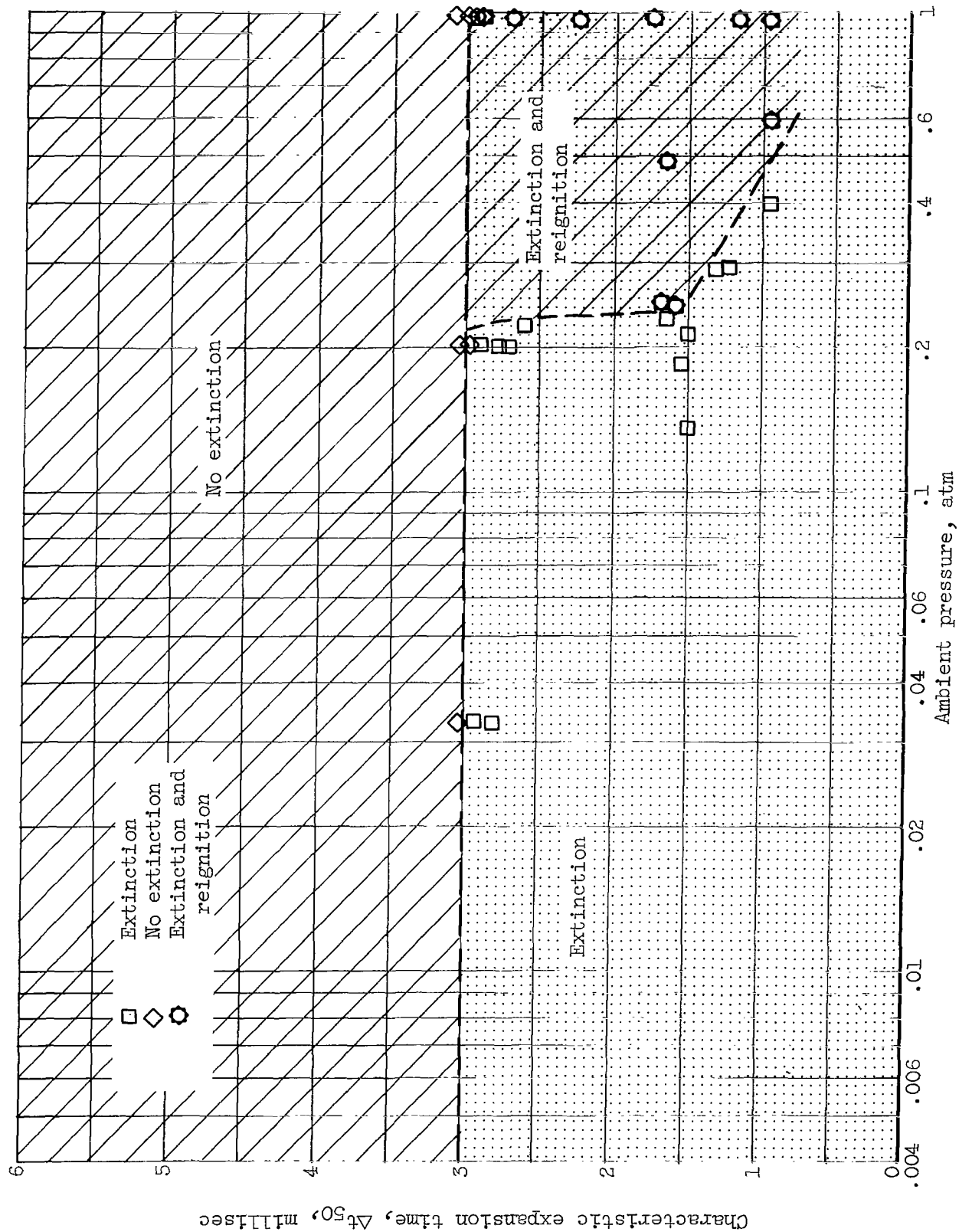


Figure 3. - Effect of ambient pressure and expansion time on extinction; composition D. Chamber pressure, 500 pounds per square inch absolute.